Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 12 (2011) 712–719

Physics Procedia

LiM 2011

Analysis of the Metal Vapour during Laser Beam Welding

S. Huber[a*], J. Glasschroeder[a], M. F. Zaeh[a]

[a]*Institute for Machine Tools and Industrial Management (iwb)*
Technische Universität München, Boltzmannstr. 15, 85748 Garching, Germany

Abstract

This article provides an insight into the radiation emission during laser beam welding of an aluminium alloy. The core issue is the development of a system to monitor the welding process of challenging alloys with respect to their chemical composition in the melt pool. This manuscript presents spectroscopic investigations used to analyse laser beam welding processes to gain insight into the metal vapour behaviour. Empirical results are accompanied by theoretical considerations about the excitation temperature and degree of different alloying elements. Both need to be investigated to develop a control system for the chemical composition of the melt pool.

Keywords: welding; composition; monitoring; alloys

1. Motivation / State of the Art

For various industries, especially for the automotive and aeronautical industry, laser beam welding has become a flexible and effective manufacturing process. The advantages of this technique are the high welding velocity, the small heat affected zone and the high level of automation. Due to further developments of products and the need to appoint new light weight materials as aluminium, the welding process has to face new problems. During the processing of these materials metallurgical defects (hot cracks, brittle welding seams, hardening cracks etc.) in the weld seam can occur. Especially cracks are a significant problem, as these lead to a lower stability of the joint. Cracks in weld seams of the investigated aluminium alloy EN AW-6060 result from the amount of silicon and magnesium in the base material (1). The detection of these cracks would be a preferred solution for quality assurance. There are a lot of quality assurance methods to identify defect products. They can be divided into three groups: online, offline and inline working control systems. These systems differ in their moment of inspection of the products during manufacturing. For a company, it is important to minimize costs and effort for detecting such defects. The most time and cost saving solution would be to control the welding simultaneously with the production (in-situ). Therefore, several solutions already exist. The utilization of them allows for detecting cracks, grooves and pores on the weld seam surface. However, there is no chance to avoid these failures because the material is already cured. During the active welding process, only process irregularities, process faults as grooves and metal spillings can currently be analysed (2). Besides this faults metallurgical defects can occur. This often results from a critical

* Corresponding author. Tel.: +49-89-289-15556; Fax: +49-89-289-15555.
E-mail address: sonja.huber@iwb.tum.de.

doi:10.1016/j.phpro.2011.03.089

chemical composition. A controlling of the weld seam composition is until now not feasible. The prevention of faults by the usage of filler material feeding (3) is actually realized, but without any knowledge of the necessary amount of additional alloying elements. The filler material can have two different effects on the process. On the one hand the wire can compensate the elemental loss by evaporation. Therefore the filler wire has to consist of a composition of the base material with a suitable amount of the element to compensate. On the other hand the composition of the wire can be configured to allow successful welding by inserting an agent element. In both cases the exact control of the chemical composition is necessary, since the concentration variations of critical elements are crucial for the welding result. Next to the laser beam welding technology, material science has become also an important field of applied research. The presented work aims for a system to monitor the chemical composition of the melt during the welding process. Therefore the spectral emission during deep penetration welding of aluminium alloy is recorded and analysed for experiments with a solid-state laser and a diode laser. The objectives of these explorations are the characterization of different elements in the excited metal vapour plume and the identification of spectral differences in the welding processes. The procedure is similar to the LIBS (laser induced breakdown spectroscopy) technique. At LIBS, a strong laser beam pulse is used to generate a local plasma on a testing material (solid or liquid state). After the pulse the relaxation of the plasma develops including the recombination of ions and electrons and the relaxation of various excited states. Latter generates the elemental lines in the radiation spectrum and allows the determination of the samples composition. The resulting lines are called *characteristic lines,* since they are specific for every element of the periodic table. Every element has various characteristic lines. The sum of all lines of a sample composed of different elements (e. g. metal alloys) is called *characteristic line spectrum.* Since the difference of the temperature in LIBS to the laser welding process is about T ~ 3000 K the generation of ions during the welding process is critical. But for excitation of single atoms the temperature in laser welding processes is sufficient. The emitted radiation during relaxation of excited states transport characteristic information about the emitting species (4, 5).

2. Spectral emissions in laser based processes

During deep penetration welding processes various kinds of spectral radiation sources have been published. The radiations can be distinguished by the wavelengths. One can identify reflected and scattered radiation having the same wavelength as the incident laser (6). Besides these two kinds also the characteristic and the thermal radiation are known (7).

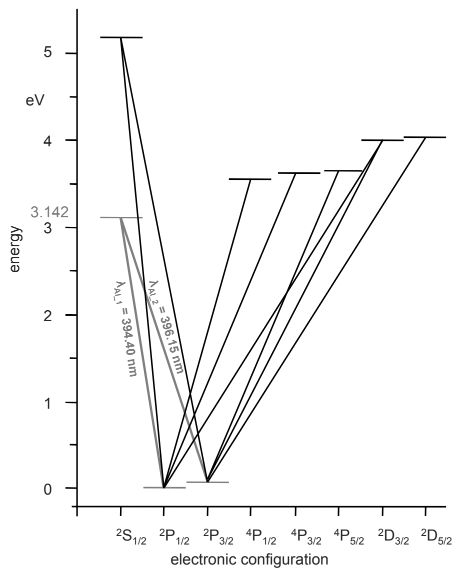


Figure 1: Detail of the spectral series of the neutral aluminium atom, where the transitions from 3.14 eV to ~0 eV are highlighted.

In Figure 1 some of the emission transitions of the neutral aluminium atom can be seen in a spectral series. The labelled transitions are measureable in the emission spectrum of the vapour during deep penetration welding. The spectral series of the elements can be deduced of the NIST Atomic Spectra Database (8) or of the Kurucz Database (9).

The generated metal vapour during deep penetration welding is the source of the line emissions. The result of inner atomic transitions, which radiate in the wavelength range of $\lambda = 260$ nm to $\lambda = 800$ nm. Beside this the melt and the heated bulk material emit continuous thermal radiation with wavelengths $\lambda > 300$ nm. In the considered laser welding processes the characteristic line emission transports information about the radiating elements in the metal vapour. As it could be shown in Zaeh et. al. (5) there is a linkage of radiating elements in the metal vapour and the elemental concentrations in the bulk material.

Free electrons e are responsible for the excitation of atoms in the metal vapour. By an inelastic collision they transfer their energy to the atoms and modify the electronic structure of the neutral species. Since the energy of free electrons during laser welding is low (10) in comparison to electron energies in LIBS (11) only the valence electrons of the atoms can be excited and their emissions analysed. Because the lifetime of the excitation status is mostly very short, they drop back to their ground state by emitting a photon. The whole reaction can exemplarily be described by the reaction equation in (1) and the deexcitation equation in (2) for the transitions of neutral aluminium atoms (Al). While Al* describes the excited neutral aluminium atom, h is Planck's constant and ν the frequency of the emitted radiation.

The excitation reaction:

$$e_{fast} + Al \rightarrow e_{slow} + Al^* \tag{1}$$

The deexcitation reaction:

$$Al^* \rightarrow Al + h\,\nu \tag{2}$$

3. Experimental procedure and materials

The measurements under realistic conditions of production were done using the experimental setup shown in Figure 2. Two spectrometers sensitive to the wavelengths $\lambda = 380$ nm to $\lambda = 880$ nm and $\lambda = 200$ nm to $\lambda = 800$ nm were utilized (AvaSpec-USB2 (Avantes), ESA 4000 (LLA Instruments GmbH)). For an absolute measurement of the spectral intensities the spectrometers were calibrated for wavelength (nm) and intensity ($\mu W/cm^2/nm$) acquisition. A workstation was attached to the spectrometers recording the data. The applied laser sources for the experiments are listed in Table 1. To ensure the comparison between measurements, a constant observing angle $\alpha = 36.5°$ and distance $d = 190$ mm must be ensured (Figure 2). During all experiments, Argon was used as a shielding-gas to prevent the oxidation of the melt and weld seams.

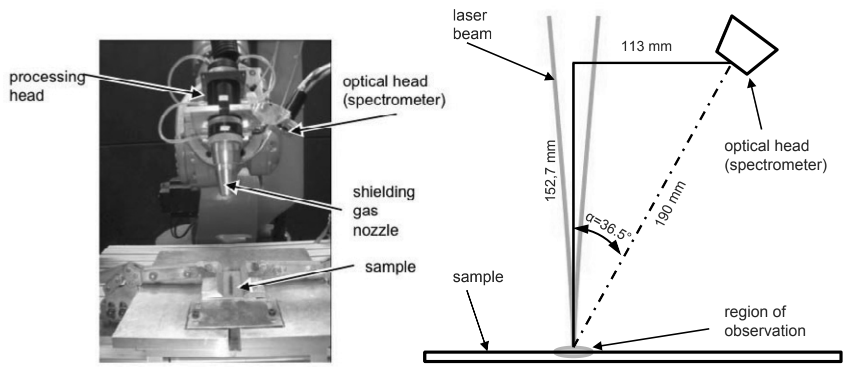


Figure 2: Experimental set-up for the measurement of the spectral emission during deep penetration welding.

The observing region of the spectrometer was arranged concentric with the laser spot on the work piece ensuring a radiation acquisition at the interaction zone. The weld seam length is an important factor in combination with the integration time of the spectrometer. Both influence the number of measurement points and spectrums per weld seam. Therefore the samples' dimensions were l = 100 mm (length), b = 100 mm (width) and a = 2 mm (thickness) allowing for a weld seam of l_w = 70 mm.

Table 1: Applied laser sources for the measurement of the spectral response during deep penetration welding.

	output power P in W	wavelength λ in nm	focal diameter in µm	power density I in 10^6 W/cm2
diode laser	6000	915, 940, 980, 1030	1000	0.8
Nd:YAG laser	3000	1064	600	1.0

The results were achieved by processing the common aluminium alloy EN AW-6060. The composition of this alloy is defined to a certain extend of mass percentage by the European standard. To gain a reference for later comparison, spectral analysis under laboratory conditions utilizing a spark spectrometer were carried out. The results of the spark spectrometer measurements for EN AW-6060 can be seen in Table 2.

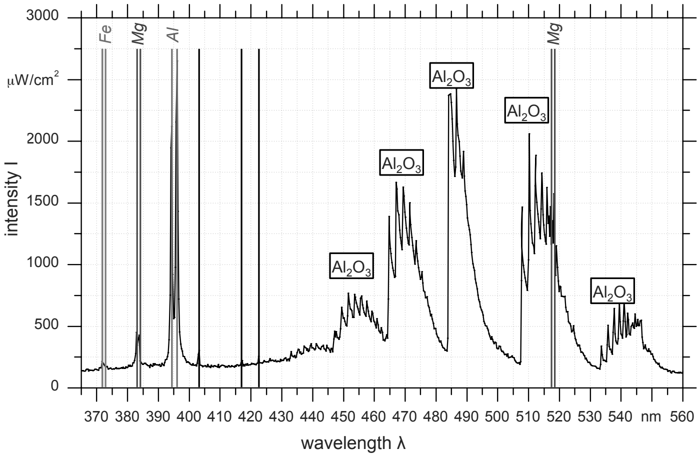
Table 2: Measured composition of the alloy EN AW–6060 by spark spectroscopy.

element	Si	Mg	Fe	Cu	Cr	Zn	Ti	Al
c in%	0.4	0.5	0.3	0.1	0.05	0.15	0.1	98.8

4. Results and Discussion

4.1. Identification of spectral lines

A method to identify spectral lines is shown in Zaeh et. al. (5). There it is demonstrated using the recorded emission spectrum of a deep penetration welding process. For identification a suitable method is necessary, since the spectral lines are used for the calculation of the excitation temperature. The characteristic line spectrum of EN AW-6060 (Table 2) was generated by welding. The experimental setup in Figure 1 was used with the spectrometer AvaSpec-USB2 (Avantes). Due to the intense process light, a neutral density filter with a transmission rate of 3 % was placed in front of the optical spectrometer head. The results of the identification process can be seen in Figure 3 and Table 3.



P_{diode} in W	λ in nm	v_w in m/min	t_{Int} in ms
6000	360 - 540	2	2

Figure 3: Characteristic line spectrum of EN AW-6060 and identification of different peaks correlating to the alloying elements.

Besides the listed species in the table, additional elements can be seen in the characteristic line spectrum. These lines belong to very small amounts of alloying elements (manganese (Mn)), impurities (calcium (Ca)) or molecules (alumina (AlO)).

Table 3: Data about the emission lines of EN AW-6060 determined during welding and verified with the NIST Atomic Spectra Database.

	wavelength λ in nm	relative intensity I in a.u.	lower energy level E_l in eV	upper energy level E_u in eV
Al I	394.34	115	0.00	3.14
Al I	396.05	120	0.01	3.14
Mg I	383.23	155	2.71	5.95
Mg I	383.83	520	2.72	5.95
Mg I	516.73	139	2.71	5.11
Mg I	518.36	139	2.72	5.11
Fe I	370.56	1290000	0.05	3.39
Fe I	371.99	-	0	3.33
Fe I	373.71	-	0.05	3.36

The described identification method is demonstrated on lines in the wavelength range from λ = 360 nm to λ = 540 nm. There are more lines below λ = 360 nm and above λ = 540 nm, which were used for the plot in the following section. To record these lines an Echelle Spectrometer (ESA 4000 - LLA Instruments GmbH) was used. It has a higher resolution for wavelength acquisition and also wavelengths λ < 360 nm could be recorded.

4.2. Boltzmann plot

Knowing the resulting temperatures, it is possible to estimate the species excited during welding. The determination of the excitation temperature is crucial to interpret the characteristic lines spectrums of the deep penetration welding process with solid-state lasers and diode lasers. The excitation temperature and the gas temperature determine the collision rate of the metal vapour particles and therefore the energy transfer. First one can be calculated by the interpretation of characteristic lines of a single element in the welded alloy. The interpretation method for determination is the so-called *Boltzmann plot*. One plot for the diode laser welding of EN AW-6060 can be seen in Figure 4. In accordance with Griem (12) the method can also be applied, if the local thermal equilibrium (LTE) condition is not fulfilled. The excitation temperature can be determined to $T_e = 5798$ K. Magnesium lines were used for the Boltzmann plot, since magnesium is known to have various electronic transitions spread in the wavelength range between $\lambda = 300$ nm to $\lambda = 480$ nm (8). The transitions of neutral magnesium atoms (Mg I) in the wavelength range from $\lambda = 260$ nm to $\lambda = 600$ nm were used. The selection criteria for appropriate characteristic lines were used in accordance with the suggested selection rules of Cremers and Radziemski (13). The failure during temperature determination by usage of the Boltzmann Plot is known to be 15 % (12). An electron temperature in deep penetration welding for aluminium can be estimated to be $T_e \sim 5000$ K.

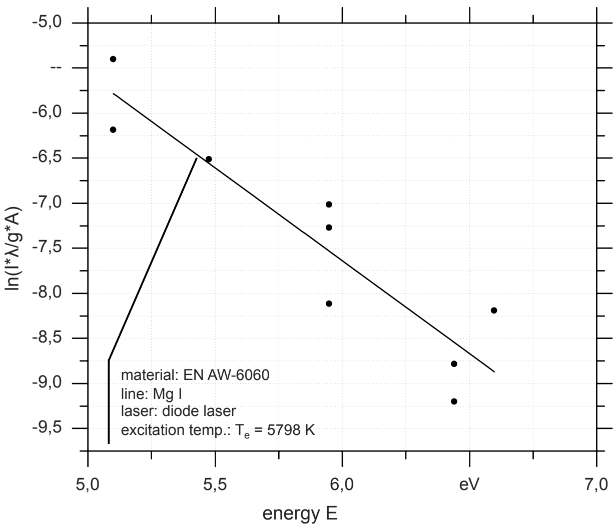


Figure 4: Boltzmann plot for temperature determination during welding of EN AW-6060 by usage of transitions of the neutral species Mg I.

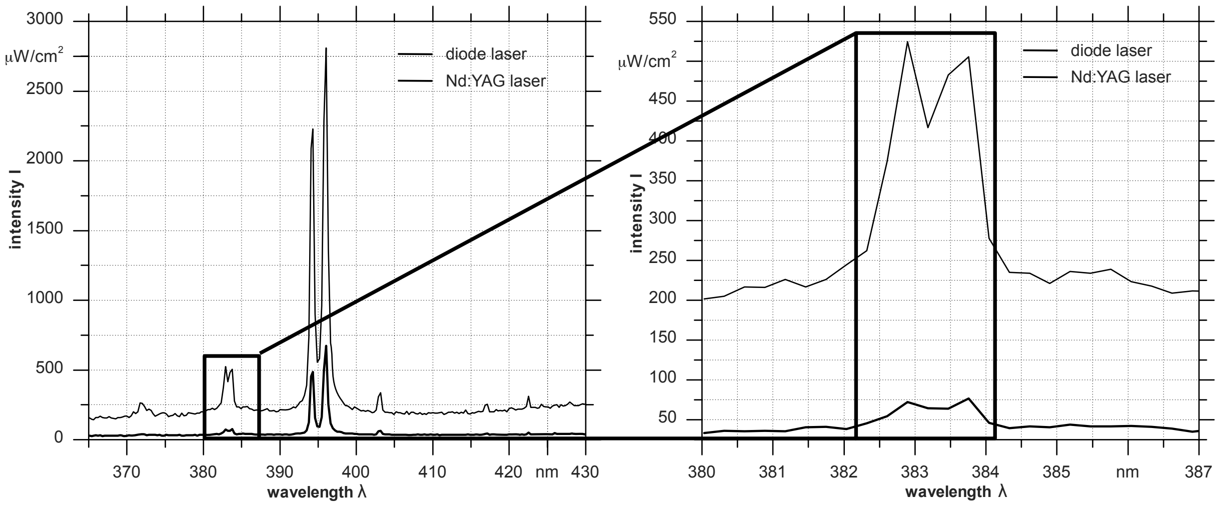
After excitation the deexciation in the form of transitions starts. The deexciation processes of many atoms (of one species) result in a measureable line intensity. This correlates with the amount of excited atoms of one species in the same electronic configuration. As it was shown in (5) that concentration variations of alloying elements during welding can be seen in intensity variations of characteristic lines. The knowledge of T_e allows the prediction of the amount of excited elements in the metal vapour and whether they can be detected. In Figure 3 the characteristic line spectrum of EN AW-6060 shows no silicon (Si) lines. In Zaeh et. al. (14) it could be shown, that silicon cannot be excited during solid-state laser and diode laser welding. As it was published in Mueller et. al. (15) the detection of silicon (Si) during CO_2 laser welding is possible. The excitation degree for one transition (and one wavelength) can be described as the ratio of excited to unexcited atoms of one species (n_k/n_0). It results from the Boltzmann equation for excitation, where g_k and g_0 represent the statistical weights. The usage of the Boltzmann equation (3) implicates the existence of LTE.

$$\frac{n_k}{n_0} = \frac{g_k}{g_0} \cdot e^{\left(-\frac{E_k - E_0}{kT_e}\right)} \tag{3}$$

As discussed above, this state is not given. Still, it allows an estimation of the excited states. Since the absence of LTE, the calculated number of excited atoms will be higher than the actual values. This means, if the calculated result of the Boltzmann equation showed that there are no excited atoms, there would not be any in the non-LTE state. The amounts of excited states in dependence of the excitation temperature were calculated for the elements silicon and magnesium. Both are common alloying elements in aluminium. At $T_e = 5000$ K the number of excited silicon atoms with a transition at a wavelength of $\lambda_{Si\_1} = 302.00$ nm is 0.0074 % of all neutral Si-atoms. Since the transition at $\lambda_{Si\_1} = 302.00$ nm has a very low relative intensity (8), the transition at $\lambda_{Si\_4} = 288.15$ nm with a high relative intensity can be examined. There can be estimated that 0.004 % Si-atoms are excited. In comparison to the Si-atoms transitions of Mg-atoms can be measured. 0.1 % of all Mg-atoms are excited for the transition at $\lambda_{Mg\_1} = 383.83$ nm at a temperature of $T_e = 5000$ K. For the transition at $\lambda_{Mg\_2} = 518.36$ nm 0.3 % and at $\lambda_{Mg\_3} = 516.73$ nm even 1.5 % Mg-atoms emit radiation. Therefore in the metal vapour of material with similar Mg and Si concentrations up to 200 more Mg-atoms than Si-atoms are excited. As it could be seen, the excitation of magnesium atoms is possible in diode laser welding of aluminium. But there are still no considerations how the excitation is by welding with solid-state lasers, which is discussed in the following section.

4.3. Differences in welding processes

During welding with the different laser sources, described in section 3, there are distinctions in the signal quality and the occurrence of single emission lines. The developing temperature during welding has a significant influence on the collision rate of the vapour particles. More excited atoms can be correlated with more radiation emitters and therefore a higher line intensity. Figure 5 shows the results, recorded during welding of aluminium EN AW-6060 executed with the maximal power output of the laser sources in Table 1. The process parameters are listed in the figure. With these adjustments, the intensity of the spectral process response is most intensive and without any saturated signals. The longer integration time of $t_{Int} = 6$ ms of the spectrometer was necessary for the Nd:YAG laser welding process to get a better signal-to-noise-ratio and to raise the signal strength without creating saturated signals. Even if the power density of the Nd:YAG laser is higher than the power density of the diode laser (Table 1), the intensity of the emissions is lower than the spectral emissions during the welding process applying the diode laser.



P_{diode} in W	$P_{Nd:YAG}$ in W	v_w in m/min	t_{Int} in ms
6000	3000	2 - 3	2 - 6

Figure 5: Spectral response of the deep penetration welding processes applying a diode laser and Nd:YAG laser.

A closer look at the spectral emission of the diode laser based welding process reveals the occurrence of single elemental peaks is more distinctive than similar spectral metal vapour emissions of deep penetration welding processes with solid-state lasers. The intensity of the emission is eight times lower than the spectral emissions during the welding process applying the diode laser. Therefore, the peaks are visible but more difficult to identify. This lets suggest, that the developed temperature in diode laser welding is higher than in solid-state laser welding.

5. Conclusion

Since the alloying elements have an influence on the mechanical properties of a weld seam, the monitoring and control allow welding of materials, where these properties depend strongly on the chemical composition. Therefore the spectral emissions during deep penetration welding were under investigation. It was shown, that spectral emissions of the evaporated metal vapours are closely linked to the temperatures. The temperature has a high impact on the vapour generation and the excitation degree of the metal vapour. It could be demonstrated, that there are restrictions in exciting alloying elements, like silicon (Si). With the results and the work presented in Zaeh et. al. (5) and Zaeh et. al. (14) an in-situ melt identification system was realized, which allows to measure concentrations and concentration variations of different alloying elements in the weld seam.

Acknowledgments

The work presented in this paper is based on investigations of the collaborative research centre SFB/TR 10 (project A11), which is kindly funded by the German Research Foundation (DFG). The authors also would like to thank the LLA Instruments GmbH for providing the analytical instruments.

Reference

[1] H. Zhang, K. Mueller and H. W. Bergmann, *Kurzzeitmetallurgie*, BIAS (2002).
[2] S. Dietrich, "Sensorik zur Schwerpunktslagebestimmung der optischen Prozessemissionen beim Laserstrahltiefschweißen," in *Lehrstuhl für Fertigungstechnik*, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen (2008).
[3] S. Huber, M. Merzkirch, M. F. Zaeh and V. Schulze, "Applications of high-power diode lasers for aluminum welding," in *SPIE - LASE 2009, High-Power Diode Laser Technology and Applications VII*, p. 71980M, SPIE Digital Library, San Jose, USA (2009).
[4] S. Katayama, "Fundamentals of Fiber Laser Welding," in *International Colloquium High Power Laser Welding 2009* A. Gumenyuk, Ed., Bundesanstalt für Materialprüfung und -forschung, Berlin (2009).
[5] M. F. Zaeh, S. Huber and R. Daub, "In-situ melt identification during laser beam welding " in *International Congress on Applications of Lasers & Electro-Optics (ICALEO) 2010*, CRC Press, Anaheim, USA (2010).
[6] M. F. Zaeh, S. Braunreuther, R. Daub and T. Stadler, "Reflected Laser Radiation - Relevance for Laser Safety?," in *6th International Conference on Laser Assisted Net Shape Engineering* M. Schmidt, F. Vollertsen and M. Geiger, Eds., Elsevier, Erlangen (2010).
[7] S. Dudeck, D. Rieger and F. Puente Leôn, "Direct observation of a laser melt pool surface," in *13th International SENSOR Conference* International Frequency Sensor Association, Nuremberg (2007).
[8] NIST, "NIST Atomic Spectra Database," National Institute of Standards and Technology (2008).
[9] L. Peter, H. Claas and R. Kurucz, "Kurucz Database," Universität Hannover (2010).
[10] H. Hügel and F. Dausinger, "Fundamentals of laser-induced processes," in *Laser Applications* R. Poprawe, H. Weber and G. Herziger, Eds., Springer, Berlin (2004).
[11] A. Bogaerts and R. Gijbels, "Fundamental aspects and applications of glow discharge spectrometric technique," *Spectrochemica Acta Part B* 53, pp. 1-42 (1998)
[12] H. R. Griem *Principals of Plasma Spectroscopy*, Camebridge University Press, Camebridge (1997).
[13] D. A. Cremers and L. J. Radziemski, *Handbook of laser-induced breakdown spectroscopy*, John Wiley, West Sussex (2006).
[14] M. F. Zaeh and S. Huber, "In-situ-Legierungsanpassung beim Laser-Tiefschweißprozess," *wt Werkstatttechnik online* 6), pp. 447-453 (2010)
[15] G. Mueller, M. Koch, W. Staudinger and T. Schuette, "Verfahren zum Laserstrahlschweißen von beschichteten Platinen," T. S. AG, Ed., Germany (2009).